

KOPIO signal and backgrounds

1. Tools (measurements and simulation)
2. Flux assumptions
3. Veto and resolution assumptions
4. Detection methods
5. Background mechanisms
6. Background from K_L^0 decays
7. Background not from K_L^0 decays
8. Signal losses aside from analysis cuts
9. Outstanding issues
10. $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ precision and sensitivity

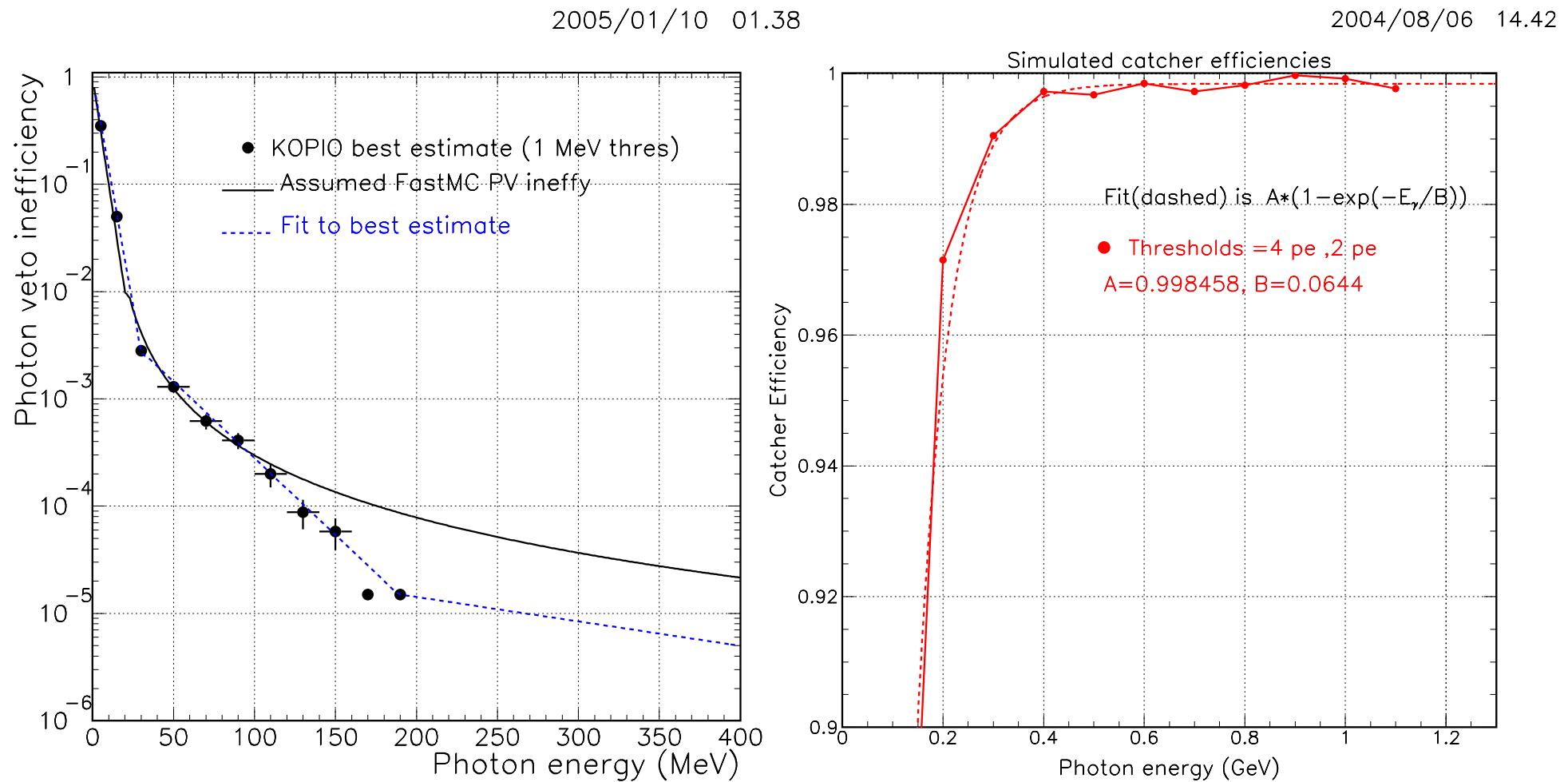
Tools

- FastMC: “Fast” simulation of KOPIO with simple geometry and parametrized responses based on measurements and/or more detailed simulation. Main tool for estimating signal and background acceptances and yields.
- GEANT3.21: Primarily used to estimate trigger, reconstruction efficiencies and to estimate signal losses due to stopped muon decays, neutron interactions, self-vetoing and vetoing by other K_L^0 in a microbunch. Also used to estimate secondary K_L^0 production in target and K_L^0 attenuation in spoiler.
- FLUKA : Investigate effect of photonuclear interactions on photon veto (PV) inefficiency.
- MCPNX : Neutron propagation and interaction
- KOPTICS, GEANT4 : ray-tracing optics in scintillator, scintillation processes.
- SLEX-LONG1D : Beam microbunch simulation

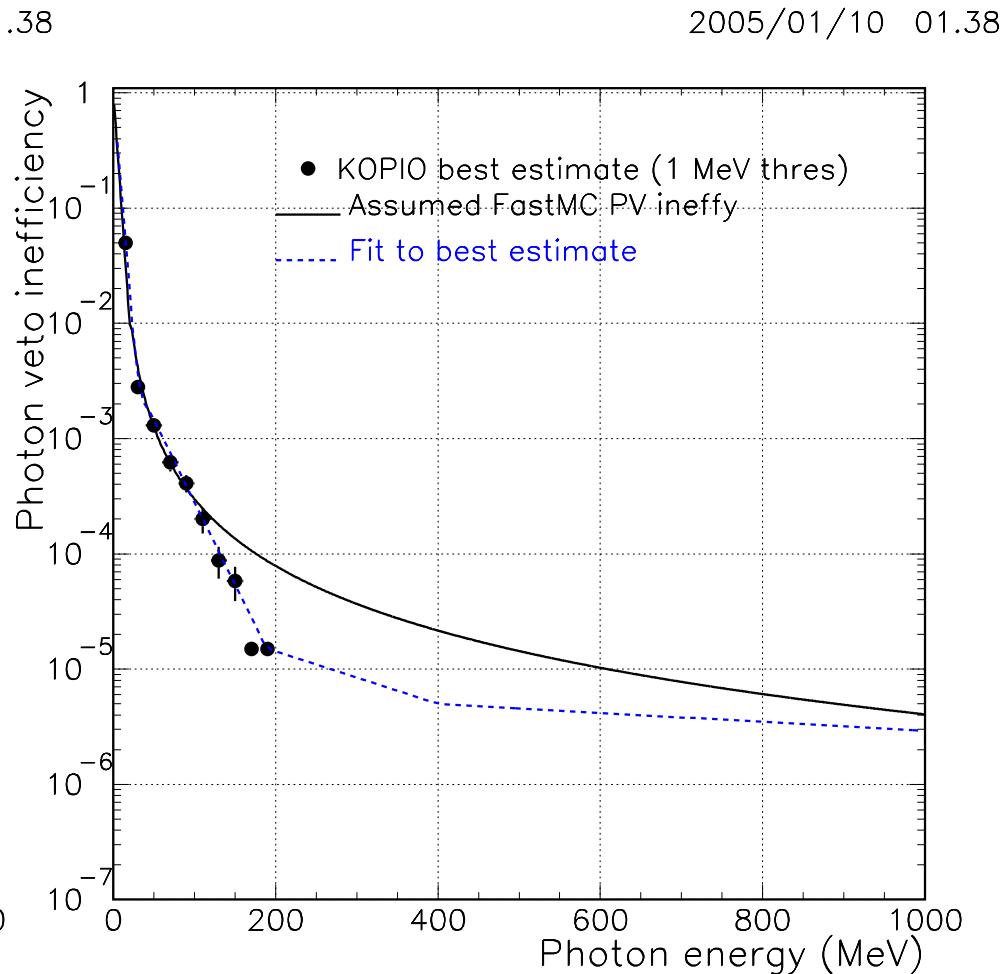
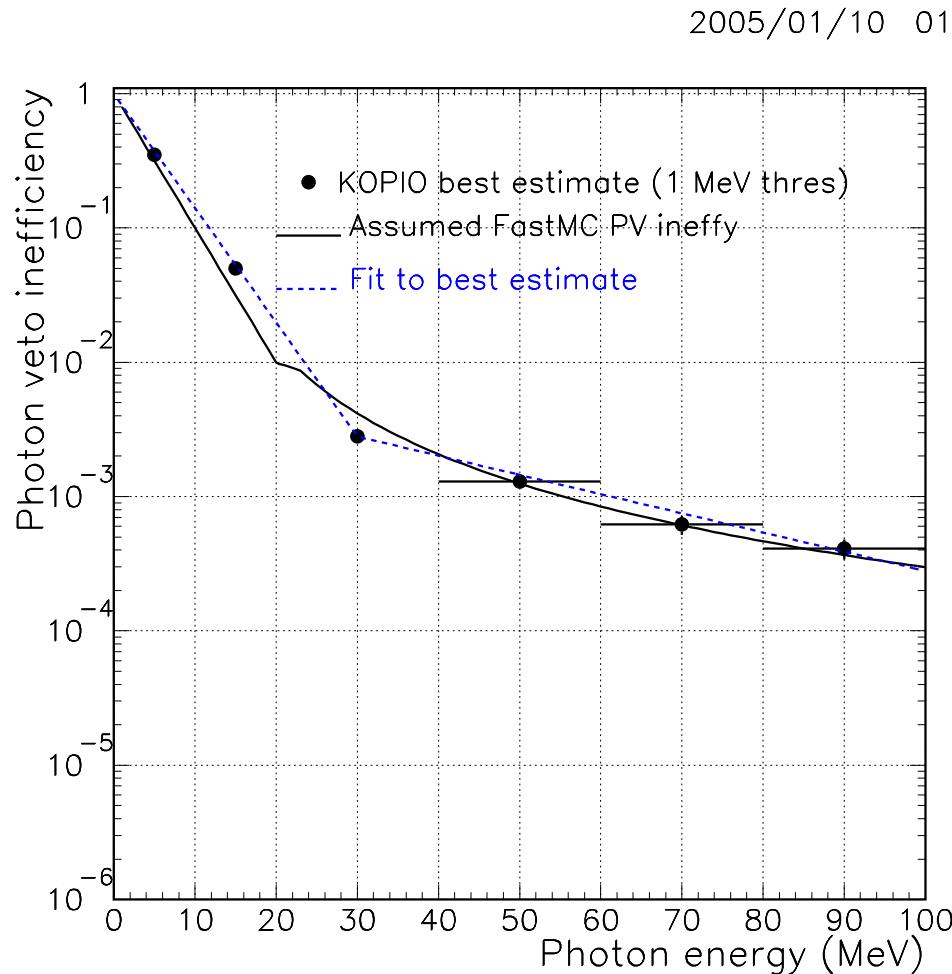
FastMC features

- K_L^0 and neutron beam momentum, angular dependence from measurements
- Extended target
- Time-structure of incident proton beam
- All $K_L^0 \pi^\pm, \mu^\pm, \pi^0$ decay modes. Decay-in-flight.
- No magnetic fields
- Preradiator(PR) and calorimeter(CAL) response parametrized from measurements
- Hermeticity assumed (except for tracks exiting decay volume via beam entrance hole).
- Photon veto (PV) inefficiency as a function of energy parametrized from measurement and simulation for the main photon veto and for the beam catcher
- Charged particle veto (CV) inefficiency as a function of species and momentum parametrized from measurements

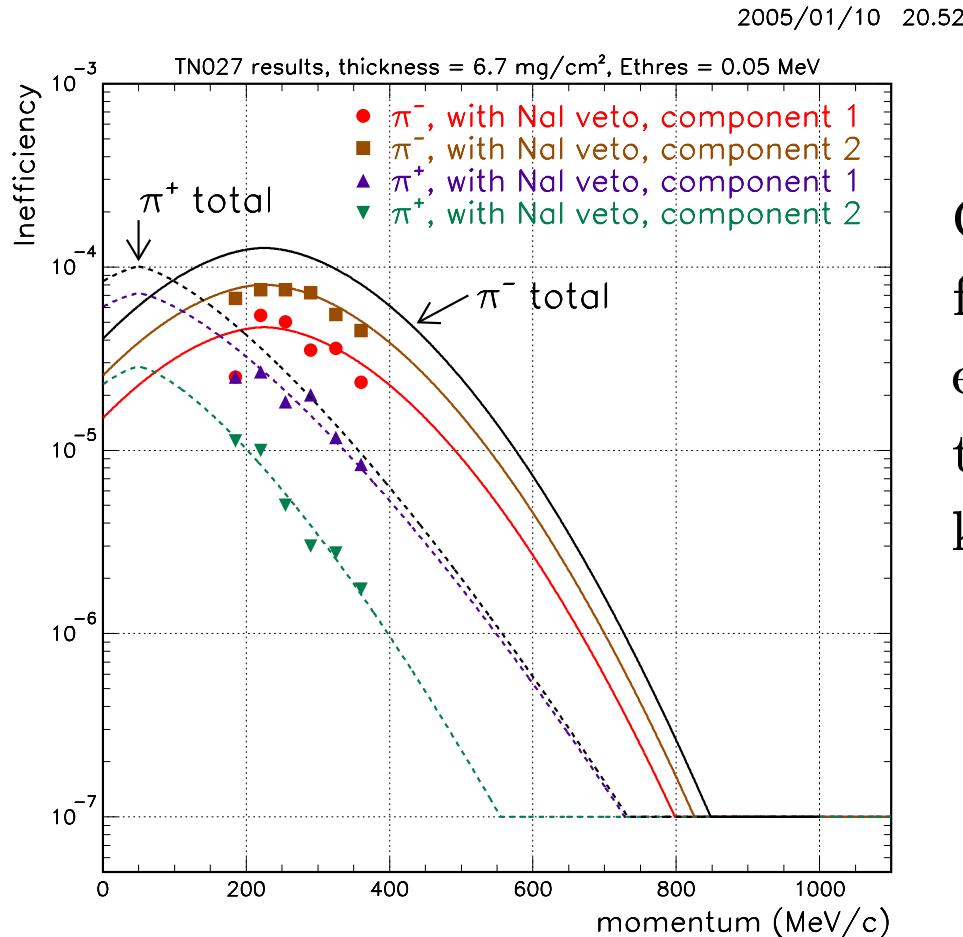
FastMC photon veto parametrizations



FastMC photon veto. Low and high E_γ range



FastMC charged pion veto parametrizations

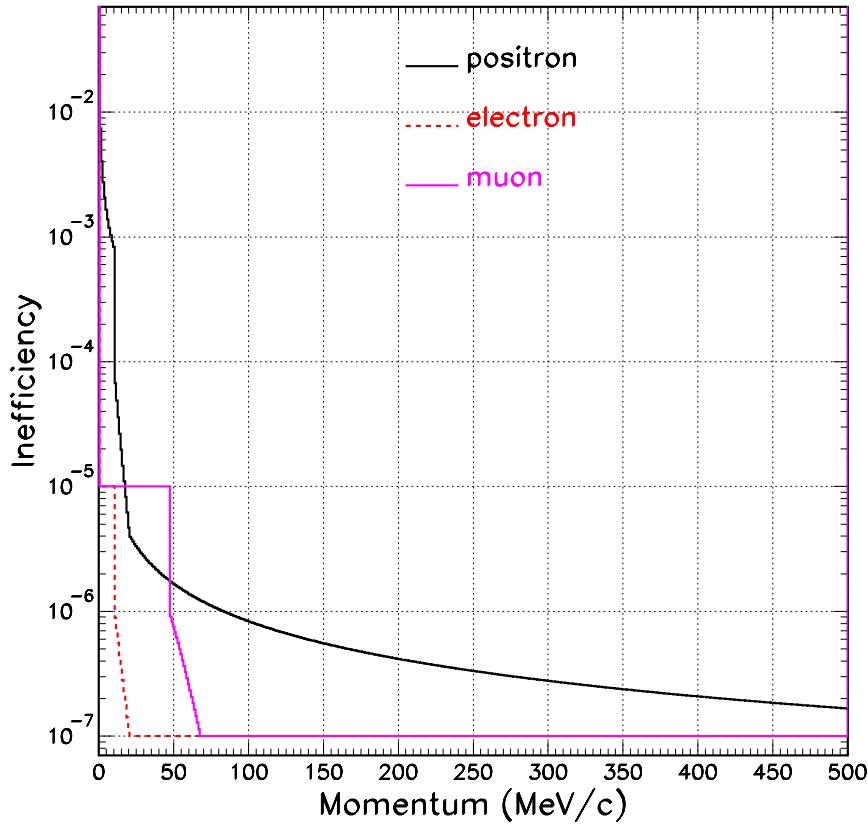


Charged pion inefficiencies taken from fits to PSI measurements and extrapolated for a dead material thickness of 6.7 mg/cm² and a 50 keV energy threshold.

Component 1 Dead material

Component 2 Threshold

FastMC μ^\pm, e^\pm veto parametrizations



Positron inefficiency from approximation to annihilation cross-section. All inefficiencies reduced by up to $\times 0.01$ due to detection by PV behind all CV elements.

Photon energy, angle and position measurement assumptions

- Energy resolution : $2.7\%/\sqrt{E(GeV)}$
- Time resolution : $90 \text{ ps}/\sqrt{E(GeV)}$
- PR angular resolution is parametrized as double gaussian as a function of photon incident angle and energy (Figure)
- PR position resolution : $0.45 \text{ cm}/\sqrt{E(GeV)}$
- Shashlyk position resolution :
 - Longitudinal 1.5cm (corresponds to 50 ps)
 - Transverse
 - * CAL 3.17 cm ($11\text{cm}/\sqrt{12}$)
 - * Barrel Veto (BV) 6.34 cm ($22\text{cm} / \sqrt{12}$)

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Prerad Resolution (mr) v. Angle (rad)

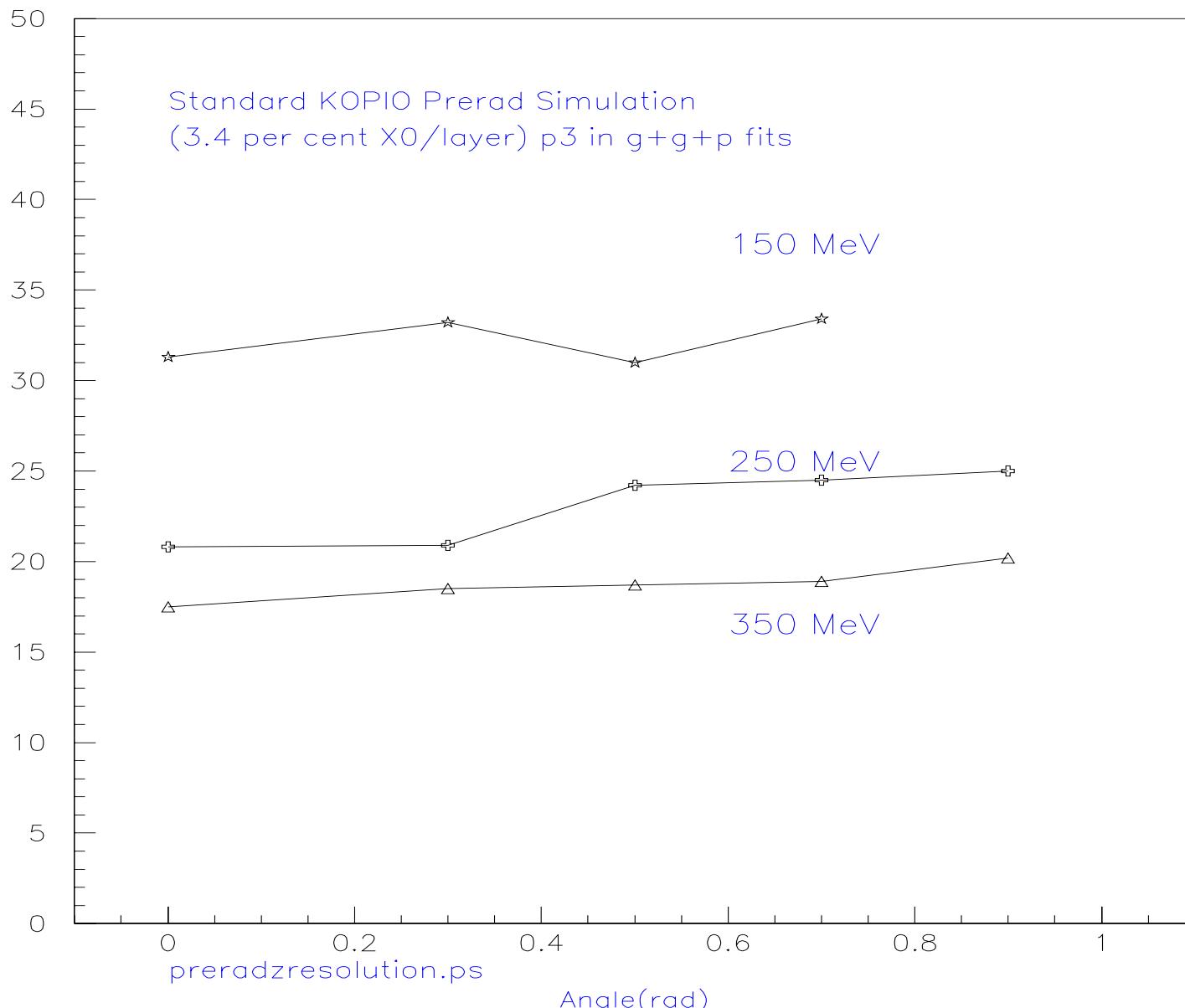


Figure A8. Narrow Gaussian angular resolution (p3) at 150 MeV, 250 MeV, and 350 MeV for the standard KOPIO preradiator with 3.4% X_0 /layer.

FastMC kinematic fitter

Two sequential kinematic fits are attempted for every pair of photon candidates using a non-linear least-squares fitter with constraints. The first fit does not impose the π^0 mass constraint, and the second fit does impose the mass constraint. The constraint of the Y-beam envelope is imposed in both fits.

The reconstructed production vertex of the π^0 (and K_L^0) is required to produce a physically meaningful value of β when the K_L^0 production point is assumed to be at the center of the target at $t=0$.

Flux assumptions

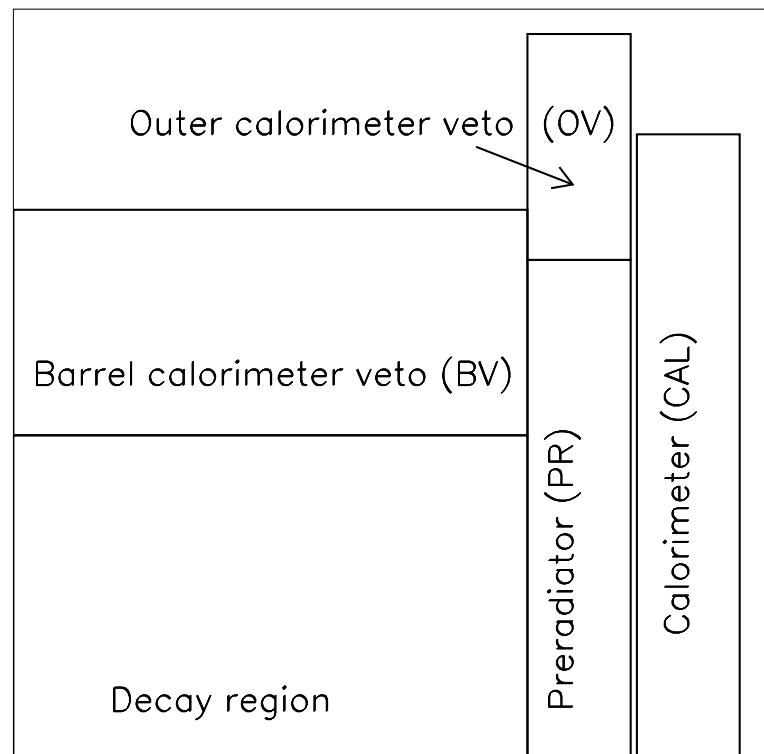
production angle	42.5°
aspect ratio	$100 \times 4 \text{ mrad}^2$
proton beam momentum	25.5 GeV/c
protons/spill	100TP
microbunch frequency	25MHz
interspill length	2.3s
spill length	5.3s
average number of K_L^0/μ bunch exiting spoiler	2.7
Hours of running	12000
K_L^0 survival factor	0.435
Useful K_L^0 decays exiting spoiler/calendar-second	1.59×10^7
Useful K_L^0 decays exiting spoiler/calendar-second takes into account all assumed losses ("K _L ⁰ survival factor").	

Detection methods considered

- | | | |
|---|---|---|
| 1 | 2γPR/CAL | both γ convert in PR, energy in PR & CAL |
| 2 | 2γPR/CAL+OV | both γ convert in PR, energy in PR,CAL & OV |
| 3 | 1γPR/1γCAL | 1 γ converts in CAL, 1 in CAL, energy in PR& CAL |
| 4 | 1γPR/1γOV | 1 γ converts in CAL, 1 in OV, energy in PR& OV |
| 5 | 1γPR/1γBV | 1 γ converts in CAL, 1 in BV, energy in PR& BV |

Results will be shown for detection methods 2, 3 and 5.

Method 1 (2γ PR/CAL) is subsumed by method 2 (2γ PR/CAL+OV) and the acceptance of method 4 (1γ PR/ 1γ OV) is very small.



Background mechanisms

Each K_L^0 decay mode is considered under the following mechanisms that can produce non-signal $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ candidates.

1. "standard" : K_L^0 decays within microbunch
2. interbunch : K_L^0 decays from interbunch K_L^0 production
3. wrap-around : K_L^0 from previous microbunch
4. accidental photons : K_L^0 decay products combined with "fake" photons from stopped muon decays or neutron-induced showers
5. merged photons : π^0 candidates from γ pairs that are too close to resolve spatially and temporally

"Fake" photon samples generated with GEANT3 and inserted into FastMC.

Merge criteria : $|\vec{x}_1 - \vec{x}_2| < 5R_M$, $R_M = 5.98$ cm, $|\Delta T_{\gamma\gamma}| < 15ns$ (CAL APD double-pulse resolution)

Main K_L^0 decay mode backgrounds

Final state	Abbreviation	Branching fraction
$\pi^0\pi^0$	kp2	9.32×10^{-4}
$\pi^+\pi^-\pi^0$	kcp3	12.59%
$\pi^\pm e^\mp\nu\gamma$	ke3g	3.53×10^{-3}
$\pi^0\pi^\pm e^\mp\nu$	ke4	5.18×10^{-5}
$\pi^0\pi^0\pi^0$	kp3	21.05%
$\pi^0\gamma\gamma$	kpgg	1.41×10^{-6}
$\gamma\gamma$	kgg	5.90×10^{-4}
γe^+e^-	ke2g	1.00×10^{-5}

Rates from other K_L^0 decays are negligible (< 0.1 events/Total K_L^0 flux).

Nomenclature: kp2-even (kp2-odd) refers to case when photon candidates come from the same (different) π^0 .

Event selection criteria - Summary of technique

Apply “setup” cuts, ideally with high signal acceptance, designed to suppress non- K_L^0 background and K_L^0 background due to veto timing considerations.

For these 3 variables,

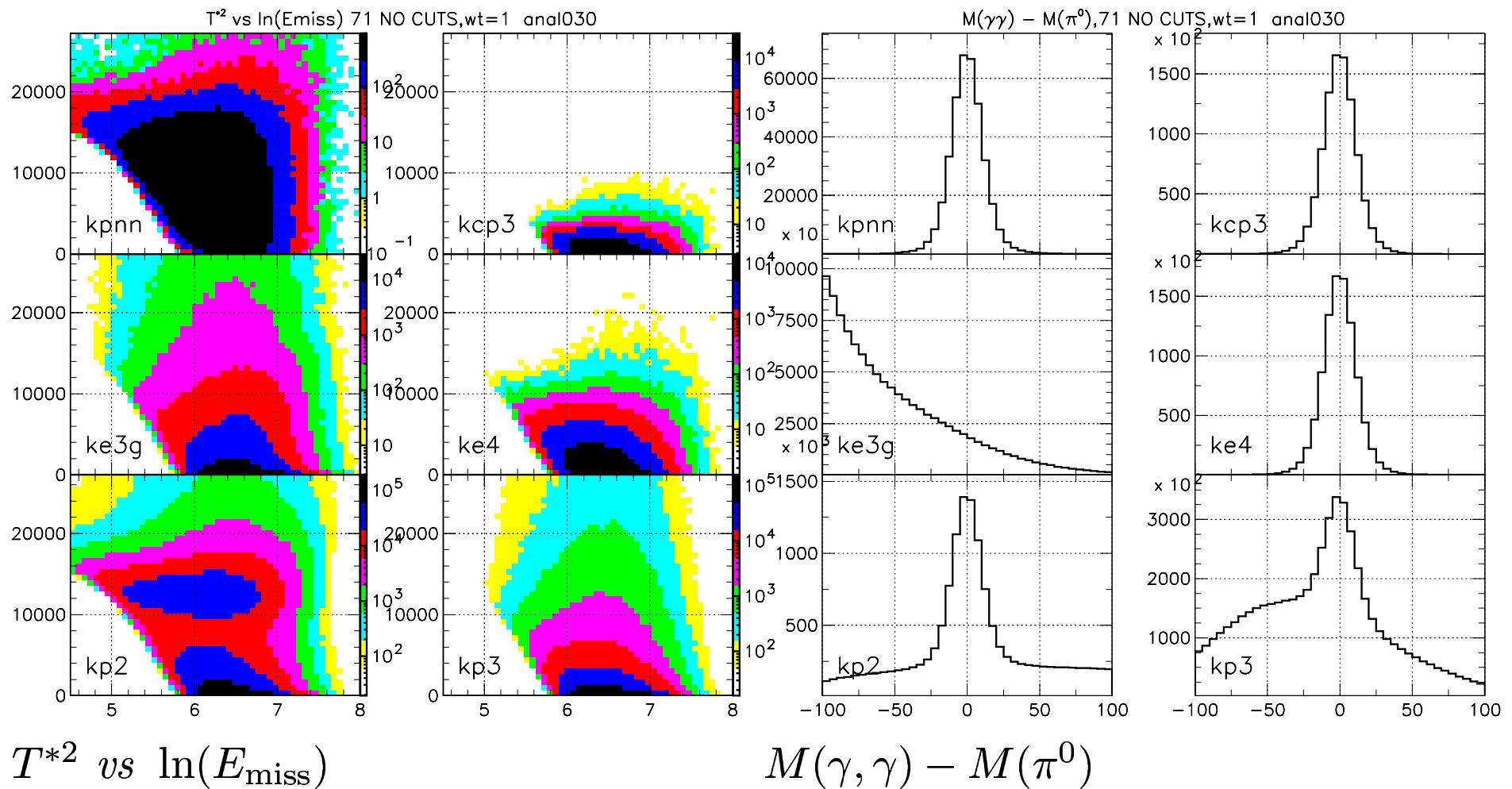
1. $M(\gamma\gamma) - M(\pi^0)$: $M(\gamma\gamma)$ is the fitted π^0 candidate mass
2. T^{*2} : T^* is the kinetic energy of the π^0 candidate in the K_L^0 CMS
3. $\ln(E_{\text{miss}})$: $E_{\text{miss}} \equiv E(K_L^0) - E(\pi^0)$ is the lab missing energy (MeV)

Use a 3-dimensional binned ‘likelihood’ method to maximize signal/background (S/B) for a given signal rate.

1. For each bin defined by the above three variables: Add up all backgrounds. Add up signal. Calculate S/B.
2. Sort bins by decreasing S/B; integrate S & B according to order of sort.
3. Define specific realizations of the general cut by noting when integrated S crosses various arbitrary thresholds.

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“Setup” cuts

Cut	Comment
$\chi^2 < 100$	Reasonable kinematic fit
$DOCA < 60 \text{ cm}$	Suppress non- K_L^0 backgrounds
$Z_1 < Z(K_L^0) < Z_2$	Suppress neutron-induced background
$P(K_L^0) > 400 \text{ MeV}/c$	Suppress K_L^0 background from next microbunch
Wrap-around	Suppress K_L^0 background from previous microbunch
$M_\nu^2 < -30000 \text{ (MeV}/c^2)^2$	Suppress background involving slow charged tracks
$DK12 < 30 \text{ cm}$	Suppress bkgd involving mis-reconstructed $Z(K_L^0)$

DOCA = Distance Of Closest Approach of 2 candidate γ

$Z(K_L^0)$ = reconstructed Z of K_L^0 candidate

Z_1 is 75cm (100cm) from US end of decay volume for $2\gamma\text{PR}$ ($1\gamma\text{PR}$)

Z_2 is 50cm (100cm) from DS end of decay volume for $2\gamma\text{PR}$ ($1\gamma\text{PR}$)

Suppressing background involving slow charged tracks

Define

$$\Delta \equiv T_{\text{hit}} - T_{K_L^0} - |\vec{x}_{\text{hit}} - \vec{x}_{K_L^0}|/c$$

where $T_{\text{hit}}, \vec{x}_{\text{hit}}$ are the time and position of veto hit, and $T_{K_L^0}, \vec{x}_{K_L^0}$ are the reconstructed time and position of the K_L^0 decay.

With no bias in reconstructed $T_{K_L^0}, \vec{x}_{K_L^0}$, expect Δ to be symmetric about zero for γ s and have a tail for $\Delta > 0$ due to slow charged tracks and decay-in-flight.

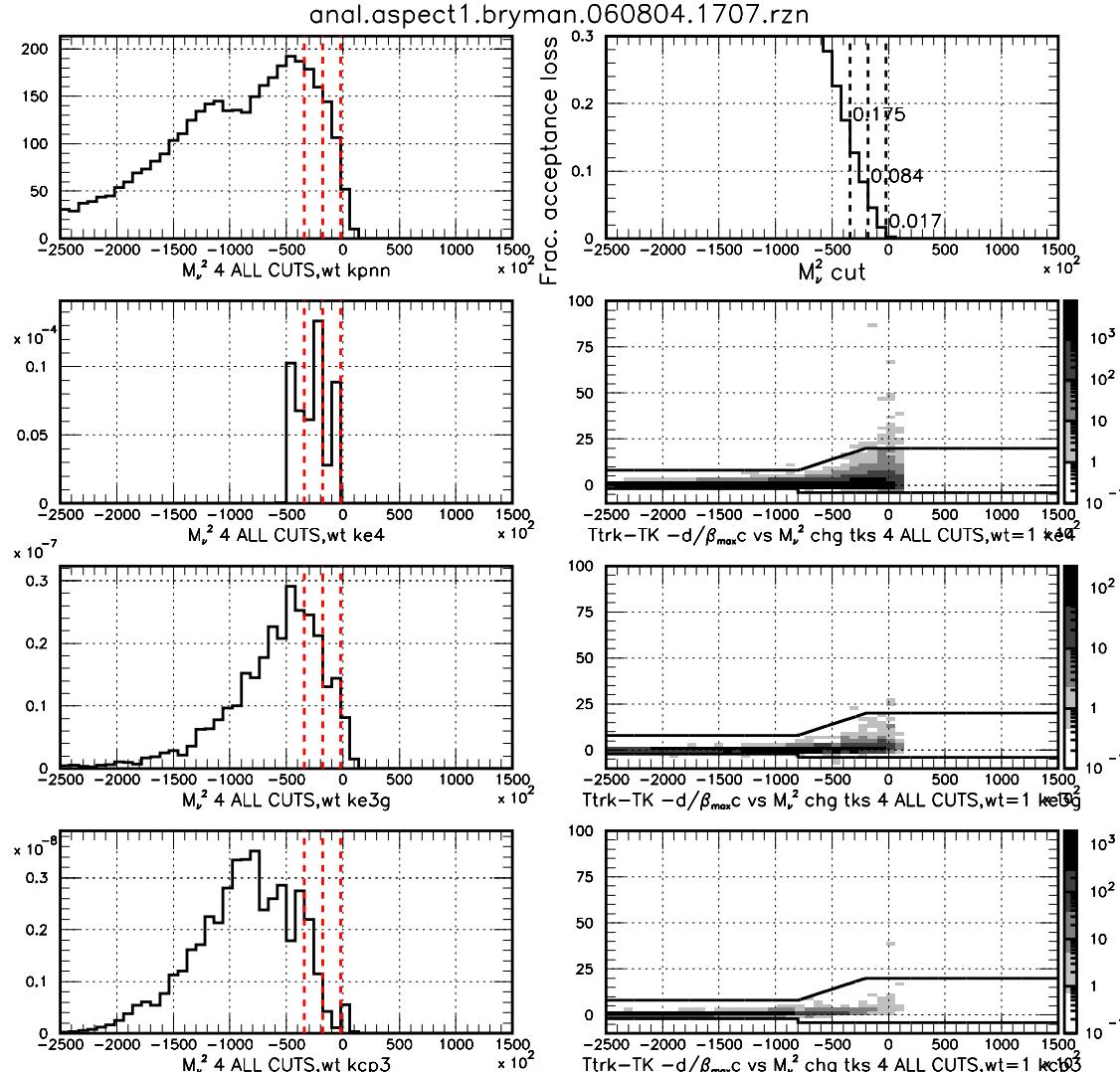
To suppress this tail, we require $M_\nu^2 < -30000 \text{ (MeV}/c^2)^2$ and apply M_ν^2 -dependent cut shown on next page, where

$$M_\nu^2 \equiv (P(K_L^0) - P(\pi^0) - P(\pi))^2 \text{ with } P(\pi) = M(\pi).$$

Note that $M_\nu^2 = M_K^2 + M_{\pi^0}^2 + M_\pi^2 - 2M_K E_{\pi^0}^* - 2M_\pi E_{\text{miss}}$, so a cut on M_ν^2 is a straight line [curve] in the $E_{\pi^0}^*, E_{\text{miss}}$ [$T^{*2}, \ln(E_{\text{miss}})$] plane.

Suppressing background involving slow charged tracks

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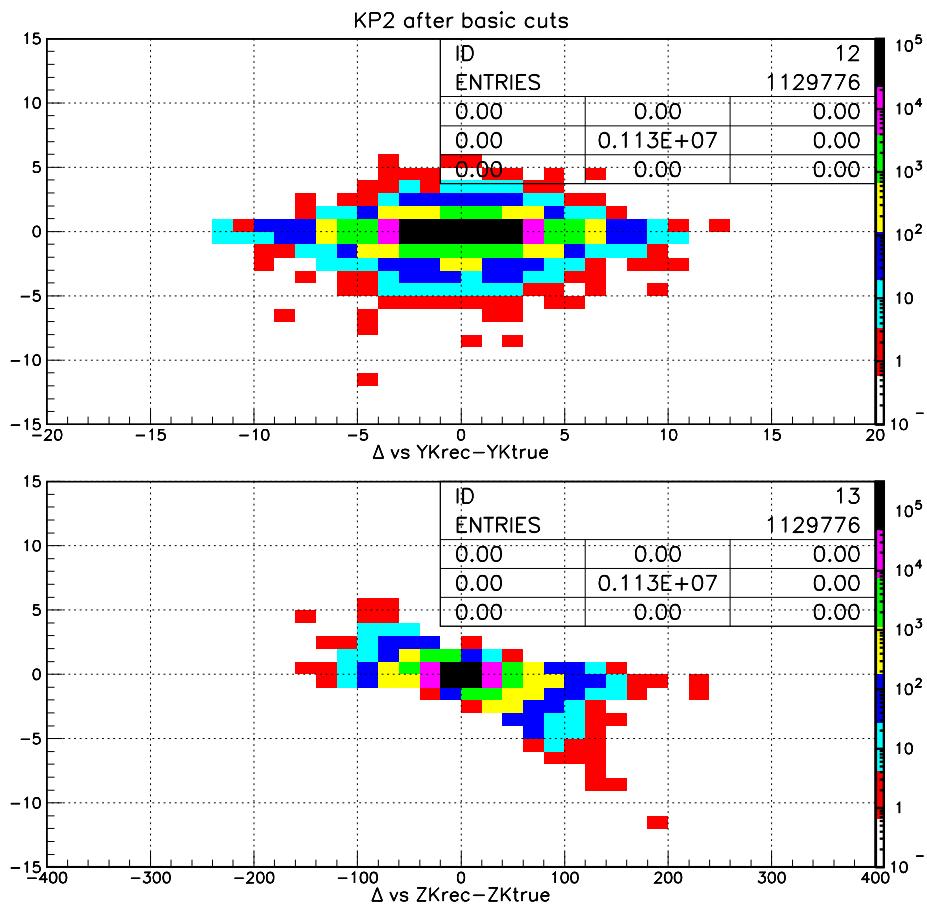


Left column: M_ν^2 distributions for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$, $\pi^0 \pi^\pm e^\mp \nu$, $\pi^\pm e^\mp \nu \gamma$, $\pi^+ \pi^- \pi^0$.

Top right: signal acceptance of M_ν^2 cuts.

Lower right: Δ vs M_ν^2 for $\pi^0 \pi^\pm e^\mp \nu$, $\pi^\pm e^\mp \nu \gamma$, $\pi^+ \pi^- \pi^0$ showing M_ν^2 -dependent cut.

Suppressing background due to misreconstructed $Z_{K_L^0}$



$Z_{K_L^0}$ may be mis-reconstructed for photon candidate pairs that do not originate from a π^0 . Examples are photon pairs from $\pi^0\pi^0$ and $\pi^\pm e^\mp \nu\gamma$.

Lower plot shows Δ vs $Z(K_L^0, \text{recon}) - Z(K_L^0, \text{true})$ for $\pi^0\pi^0$ after basic cuts ($|M_{\gamma\gamma} - M(\pi^0)| < 20$ MeV, $\chi^2 < 100$, DOCA < 60 cm, $1015 + 75 < Z(K_L^0) < 1415 - 50$ cm) and the photons are required to pass fiducial cuts to satisfy 2 γ PR/CAL. DOCA is the distance of closest approach between the measured photon trajectories.

Misreconstructed $Z_{K_L^0}$ for 2γ PR detection mode

The misreconstruction is caused by large scattering in Y direction on 1 γ coupled with energy mismeasurement of one or both γ .

In particular, it occurs when one photon has a relatively small Y angle. When the γ s are not from a π^0 and the energy is mismeasured, imposing the π^0 mass constraint shifts the reconstructed $Z_{K_L^0}$.

Note that we preferentially accept $Z(K_L^0, \text{recon}) > Z(K_L^0, \text{true})$, because $P(K_L^0, \text{recon}) > P(K_L^0, \text{true})$ and $E_{\text{miss}}(\text{recon}) > E_{\text{miss}}(\text{true})$.

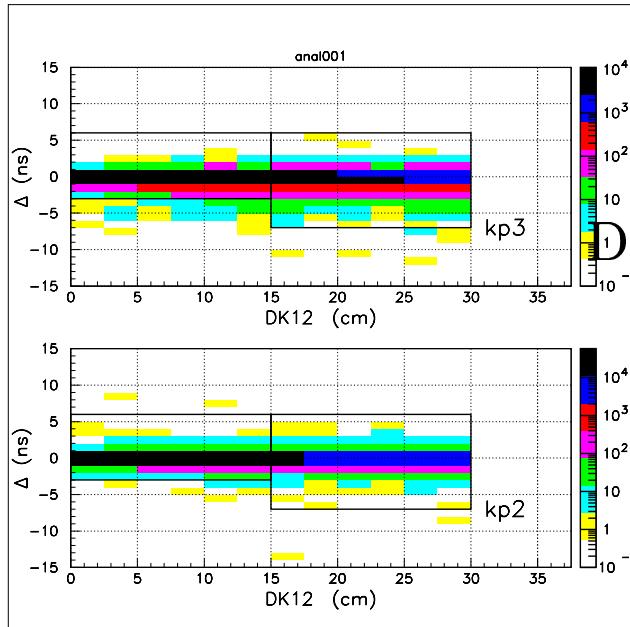
There is also correlated effect that makes Δ more negative for $\pi^0\pi^0$: $Z(K_L^0, \text{recon}) > Z(K_L^0, \text{true})$ sometimes implies $d(\text{recon}) > d(\text{true})$ for $\pi^0\pi^0$ -odd with backward-going photons. ($d \equiv |\vec{x}_{\text{hit}} - \vec{x}_{K_L^0}|$)

Misreconstructed $Z_{K_L^0}$ for 2γ PR detection mode

Define $\Delta Z \equiv Z(K_L^0, \text{recon}) - Z(K_L^0, \text{true})$

The two useful variables to identify large $|\Delta Z|$ are

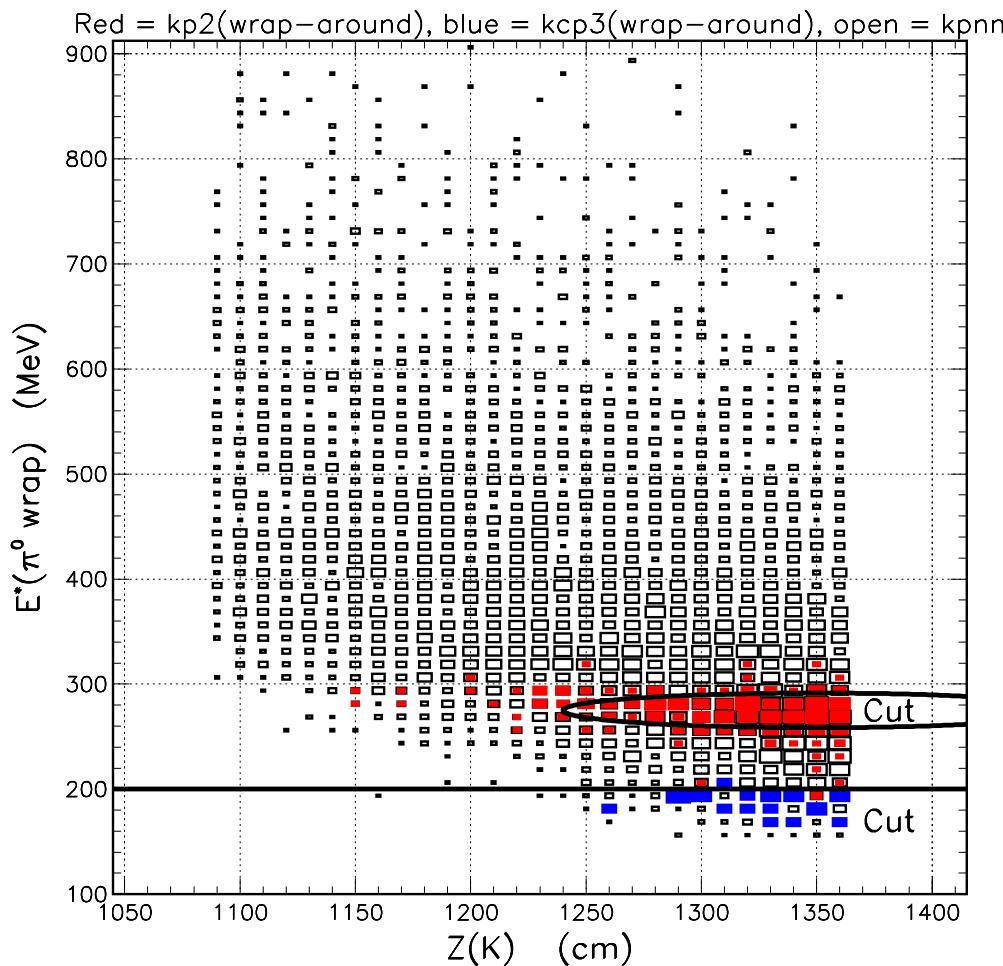
1. DOCA1+DOCA2 where DOCA*i* is the distance of closest approach of the *i*th measured photon to $Z(K_L^0, \text{fit2})$, and
2. $Z_1(K_L^0) - Z_2(K_L^0)$ where $Z_i(K_L^0)$ is the recon. $Z_{K_L^0}$ from the *i*th fit. Fit 1(2) fits the 2γ to a common vertex without(with) a π^0 mass constraint.



$$DK12 \equiv \sqrt{(DOCA1 + DOCA2 - 5.)^2 + (Z_1(K_L^0) - Z_2(K_L^0))^2}$$

Reject events with $DK12 > 30$ cm and use
DK12-dependent Δ cut on remainder

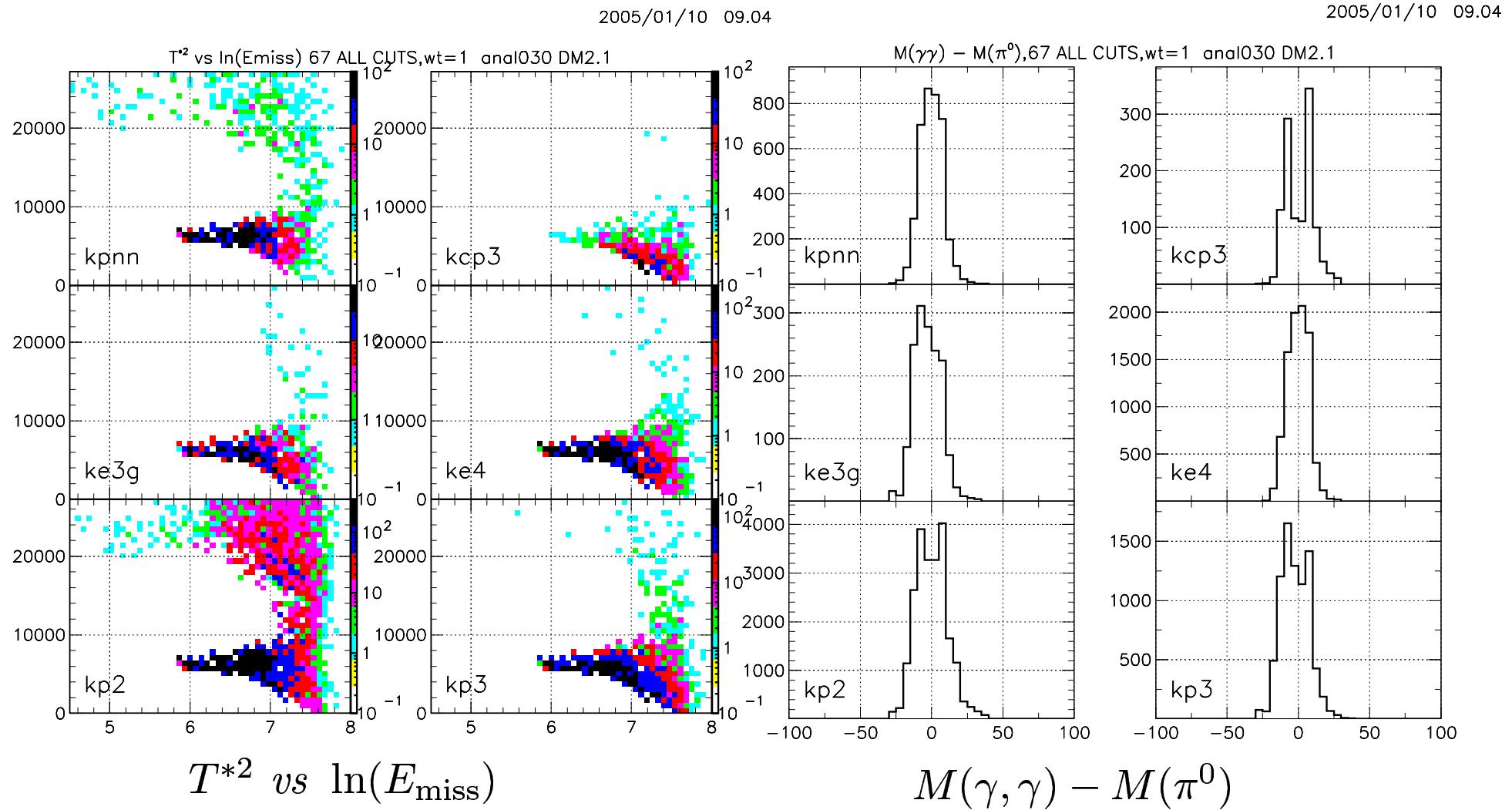
Wrap-around cut



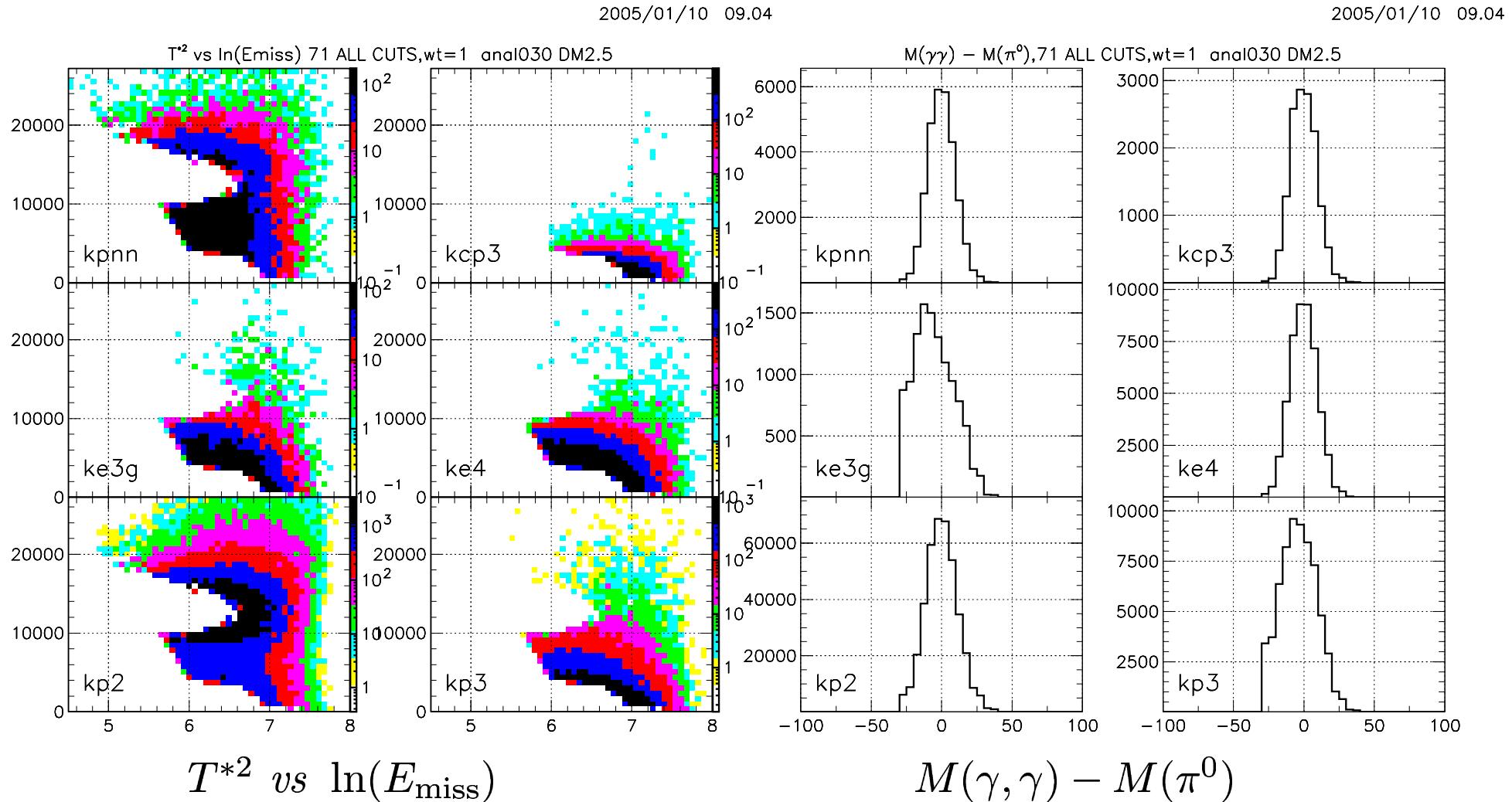
Wrap-around background occurs when a slow K_L^0 produced in the previous microbunch decays in the current microbunch.

The figure shows $E^*(\text{wrap})$ vs $Z(K_L^0)$ for signal(produced in current microbunch) and kp2 and kcp3(produced in previous microbunch) where $E^*(\text{wrap})$ is the energy of the π^0 candidate calculated as if it were produced in the previous microbunch.

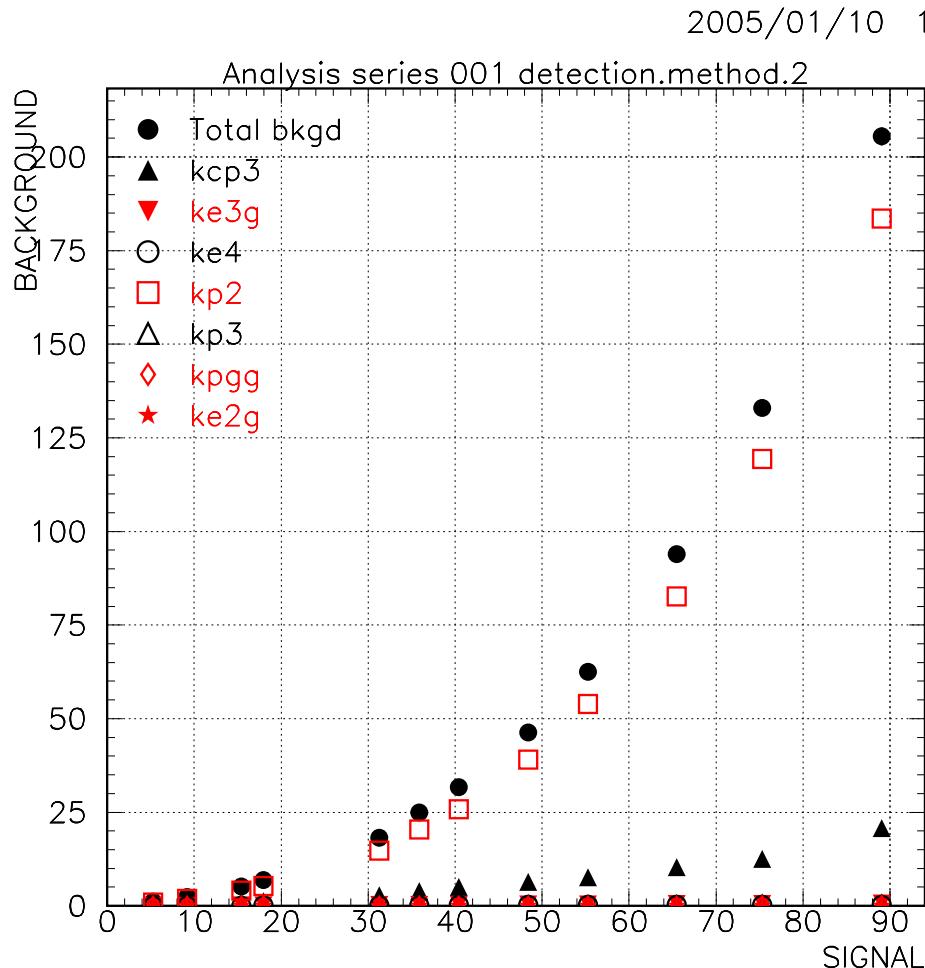
Results of optimization procedure, 2γ PR/CAL+OV, tightest cuts



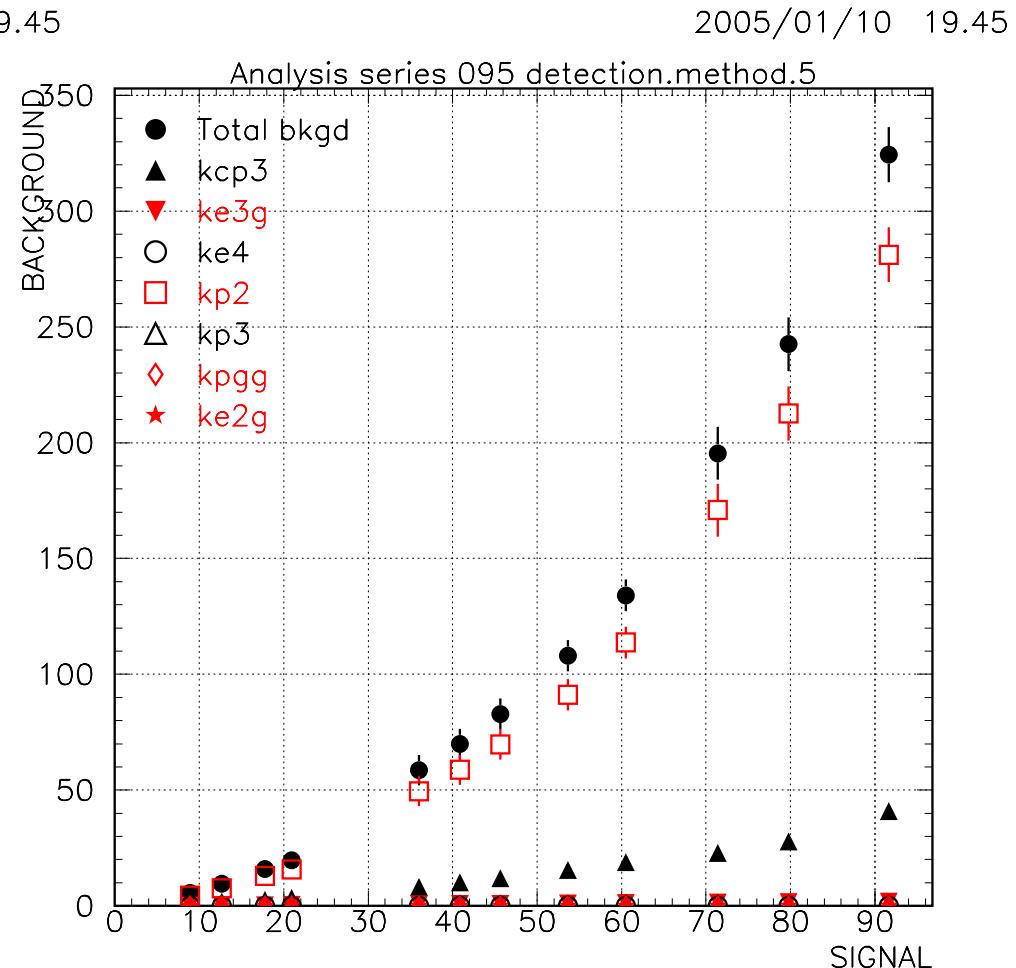
Results of optimization procedure, 2γ PR/CAL+OV, loosest cuts



In-bunch backgrounds 2γ PR/CAL+OV and 1γ PR/BV detection modes



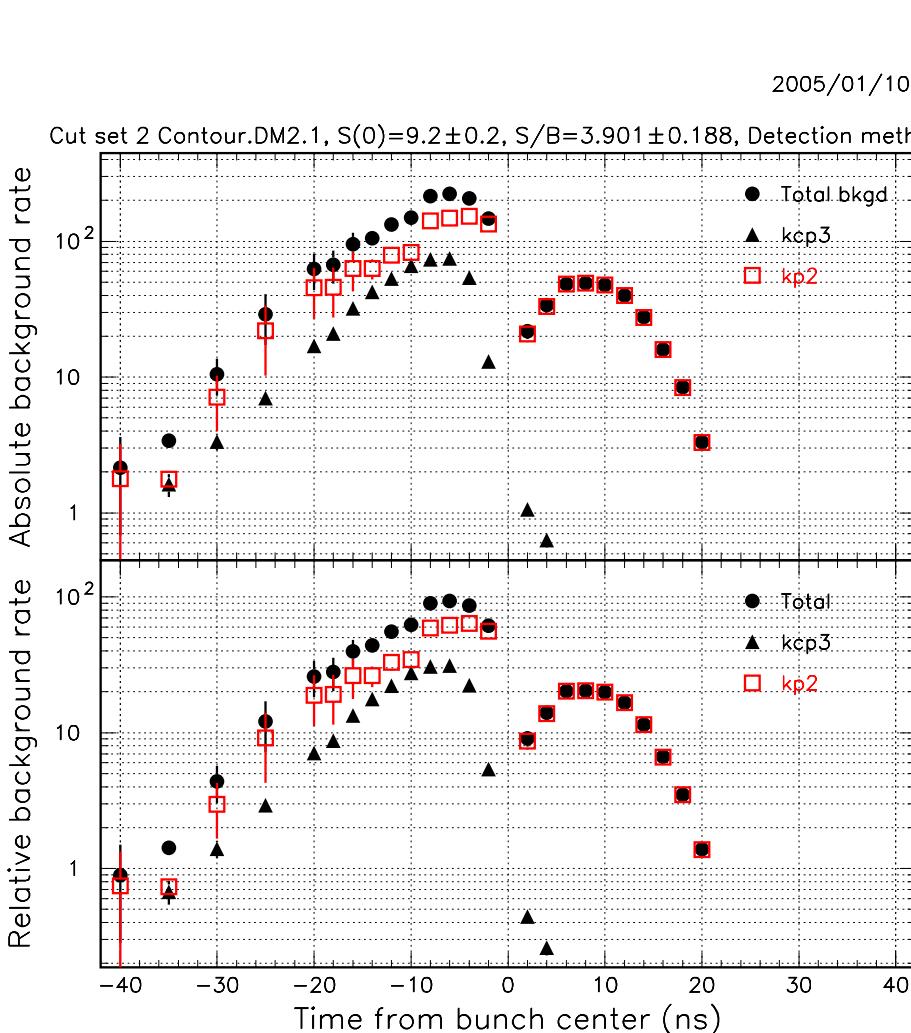
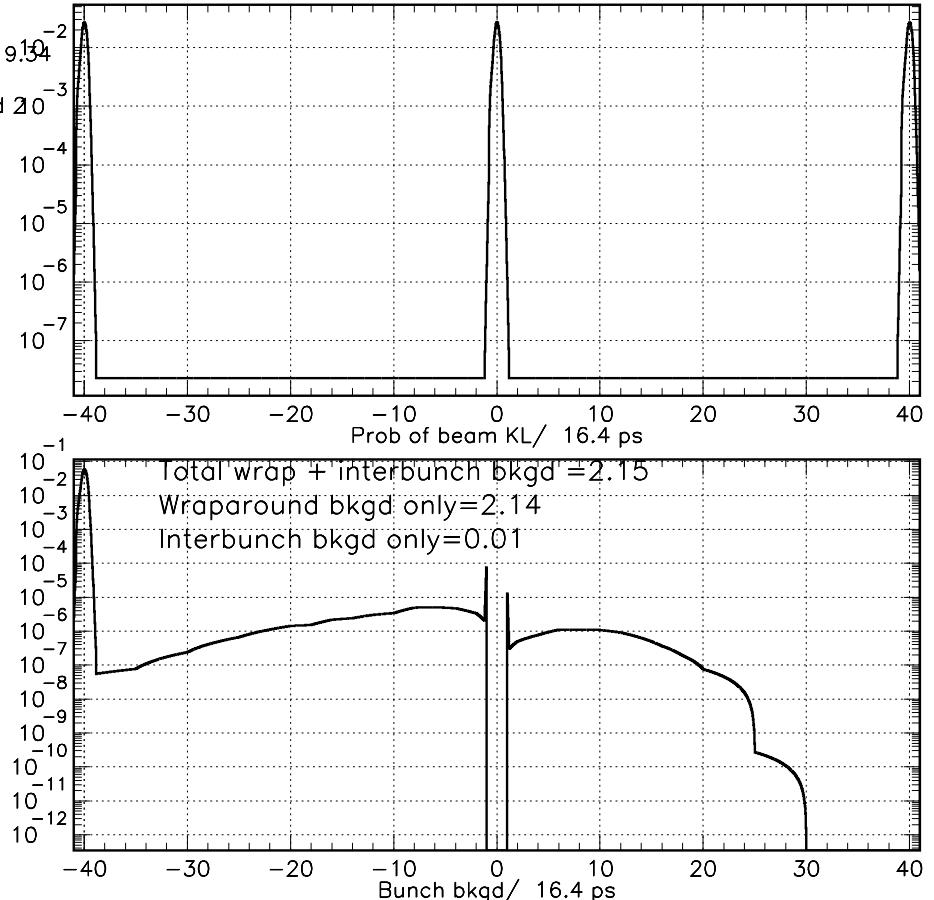
Background *vs* Signal
 2γ PR/CAL+OV



Background *vs* Signal
 1γ PR/BV

2 γ PR/CAL+OV detection mode, interbunch and wrap-around rates

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Cut set 2 Contour.DM2.1, $S(0)=9.2\pm 0.2$, $S/B=3.901\pm 0.188$, Detection method 2

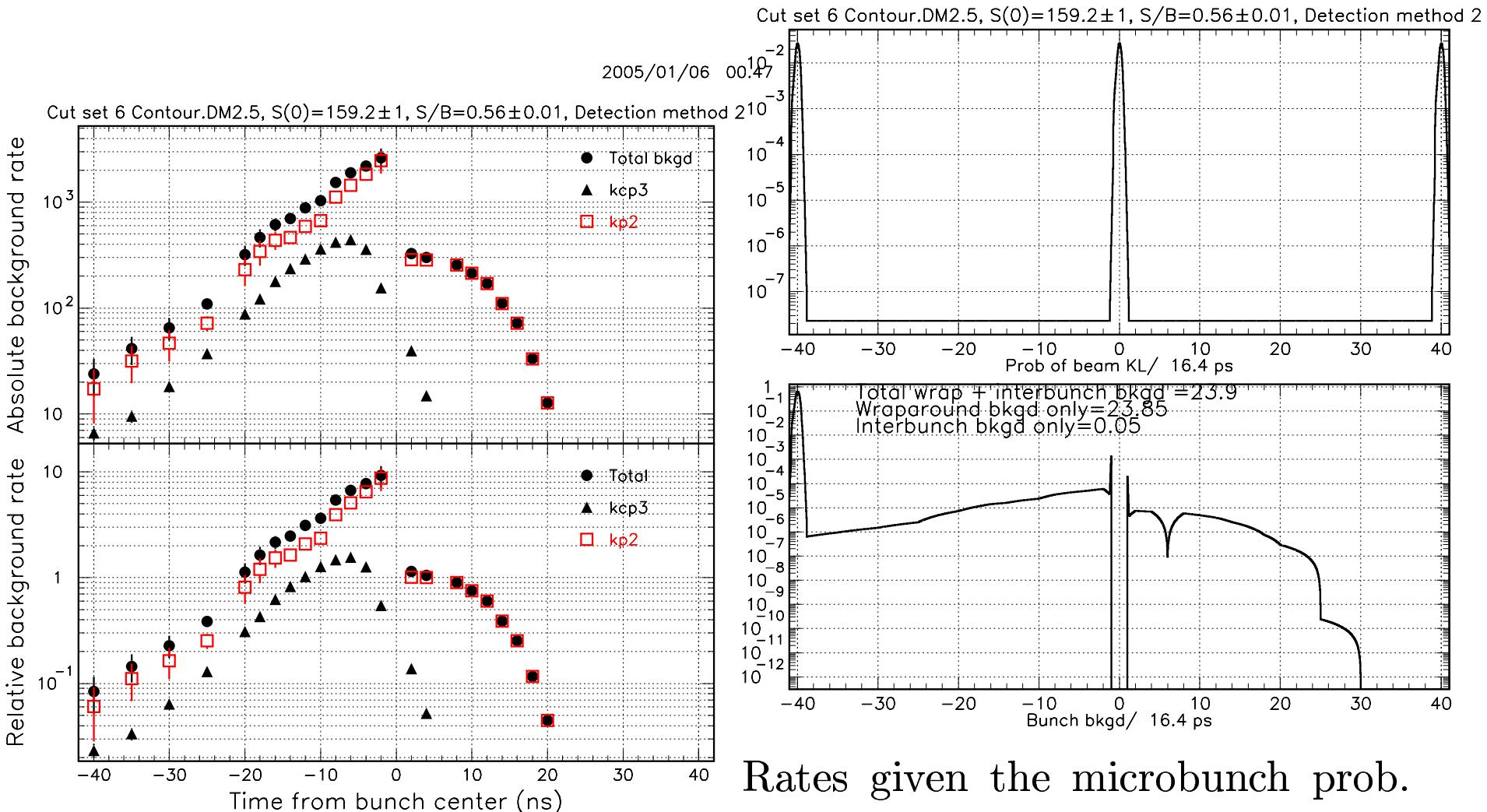
Rates given the microbunch prob.
distribution.

Wrap-around bkgd = 2.14, Inter-
bunch = 0.01

Tightest cuts

2 γ PR/CAL+OV detection mode, interbunch and wrap-around rates

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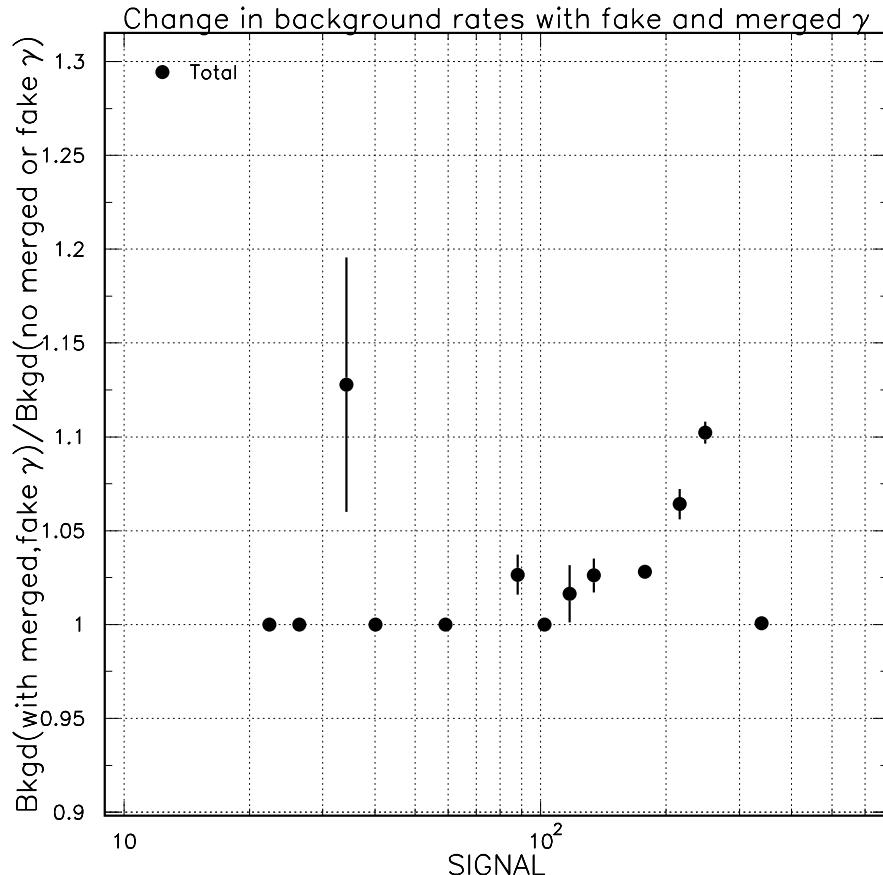


Loosest cuts

Rates given the microbunch prob.
distribution
Wrap-around bkgd = 6.42, Inter-
bunch = 0.02

2 γ PR detection mode, rates with fake & merged γ s

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Fake and merge rates increase background by 1.025 ± 0.025

Bkgd(with fake & merged γ s)/Bkgd(no fake & merged γ s) vs Signal

Veto detector studies

1. Effect of catcher double-pulse resolution
2. Rates compared to infinite PV and CV gates
3. Effect of position of CV in decay region
 - “far” position - veto lines inner wall of decay region
 - “near” position - veto has half-dimensions 111cm × 50 cm

Effect of catcher double-pulse resolution (δt)

Catcher would be blind if γ from K_L^0 arrives too close in time to γ from target produced by proton beam (“ γ flash”).

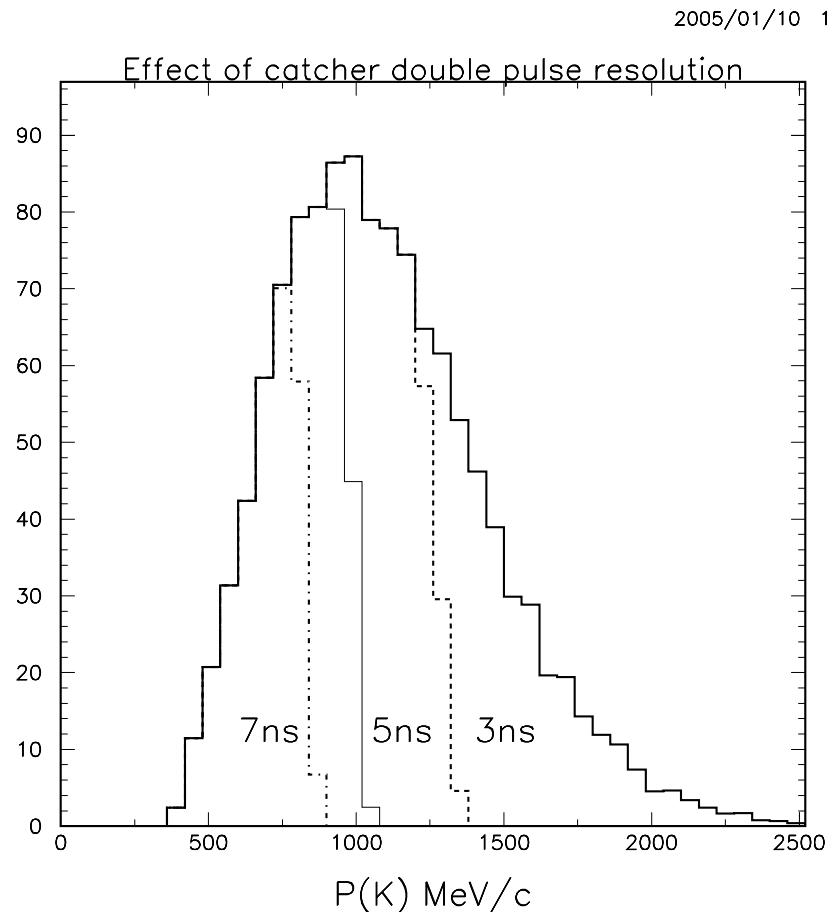
Time of γ at catcher from K_L^0 is $t_c = t_K + d/c$ where d is distance from K_L^0 decay to catcher. Approximate $d \approx z_{\text{catcher}} - z_K \equiv z_c - z_K$ where z_{catcher} is US end of catcher.

Time of γ flash at catcher is $t_f = z_c/c$, so arrival time difference is $\delta t = t_k - t_f = t_k + (z_c - z_K)/c - z_k/c = t_k - z_k/c = t_k(1 - \beta_z)$.

The δt cut is effectively a high momentum cut and removes K_L^0 for which we otherwise have the best veto efficiency.

Next page shows momentum bite as a function of a cut on δt .

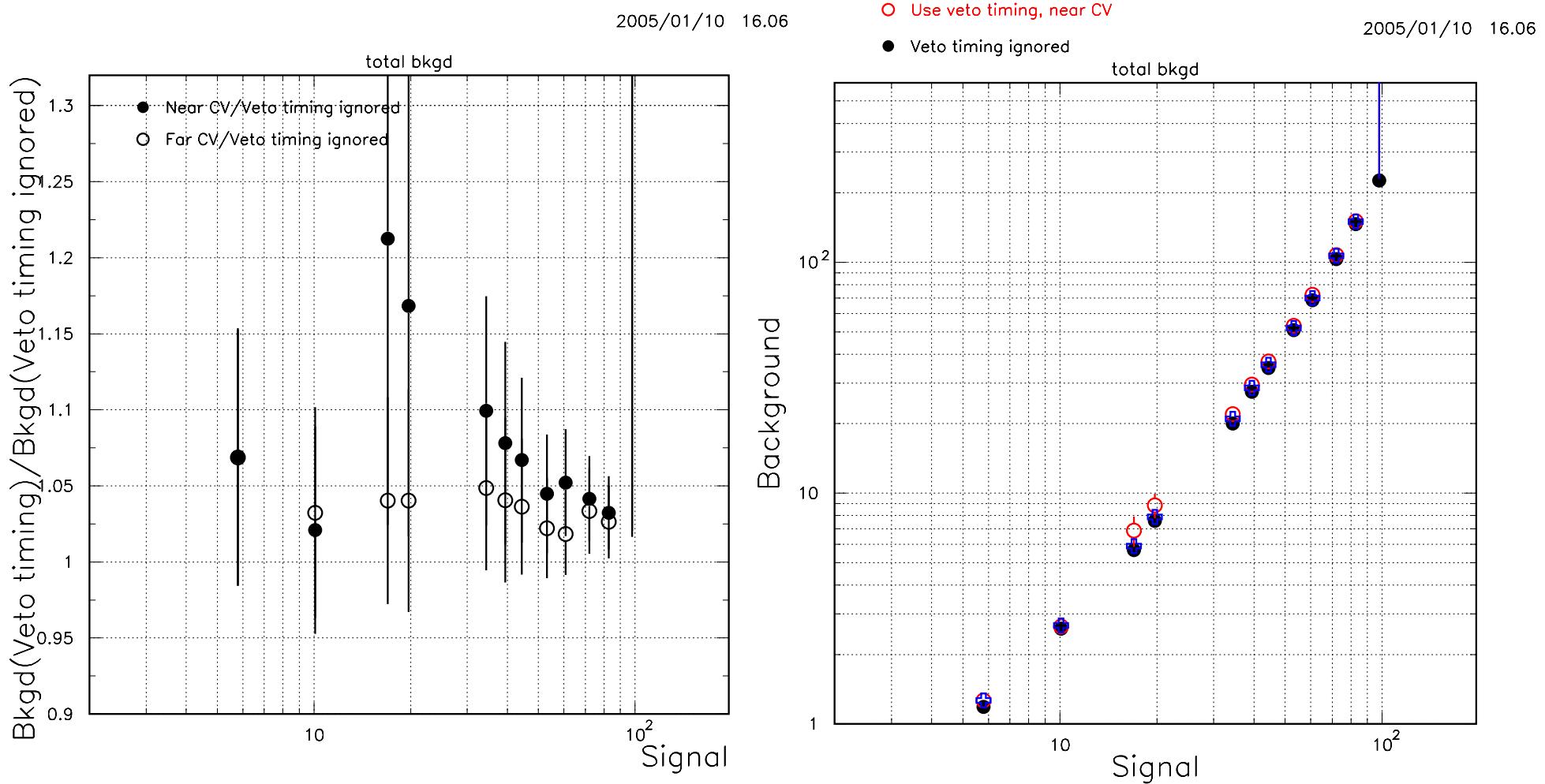
Effect of catcher double-pulse resolution



To recover the events ($P(K_L^0) > 1300 \text{ MeV}/c$) when the catcher is blind, we make a kinematic fit using the Kp2 hypothesis and calculate the position of the missed photon at the catcher. A cut with 50% acceptance suppresses Kp2 background by 20×; the events can be recovered without reducing S/B.

A more restrictive catcher veto algorithm with ~ 0.05 inefficiency would recover all events without reducing S/B.

Rates with veto gates, 2γ PR detection mode



Background rate with/without veto timing.

B vs S with & without veto timing and CV at near, far positions.

(Mostly) non- K_L^0 background sources

1. K^+ contamination of beam: < 0.013 of signal rate without considering kinematic suppression or divergence to due B field.
2. $K_L^0 \rightarrow K^\pm e^\mp \nu$: < 0.001 of signal rate
3. $nN \rightarrow \pi^0 X$: negligible production from residual gas in decay volume if pressure < 10^{-6} Torr. Requirements on reconstructed $Z(K_L^0)$ suppress rate from upstream wall to < 0.01 of signal rate.
4. \bar{n} : far smaller than neutron background.
5. Hyperons: < 0.002 of signal rate.
6. Fake photons: < 0.05 of signal rate assuming $\sim 10^{-3} \times 10^{-3}$ suppression from (vetoing) $\times (\gamma/n$ discrimination from shower reconstruction.)
7. Two K_L^0 giving a single candidate: negligible due to veto opportunities
8. $(K_L^0 \rightarrow \pi^\pm X) \times (\pi^\pm \rightarrow \pi^0 e^\pm \nu)$: < 0.05 of signal rate

Signal losses other than analysis cuts

Losses include an estimated range of uncertainty.

- Independent of instantaneous rate

$0.88^{+0.05}_{-0.10}$ Self-veto

$0.92^{+0.04}_{-0.02}$ Photon absorption in vacuum vessel

- Rate dependent (veto rates assume optimal spill length)

0.60 ± 0.02 Vetoing by other K_L^0 in the same microbunch

0.875 ± 0.013 Vetoing by stopped muon decays

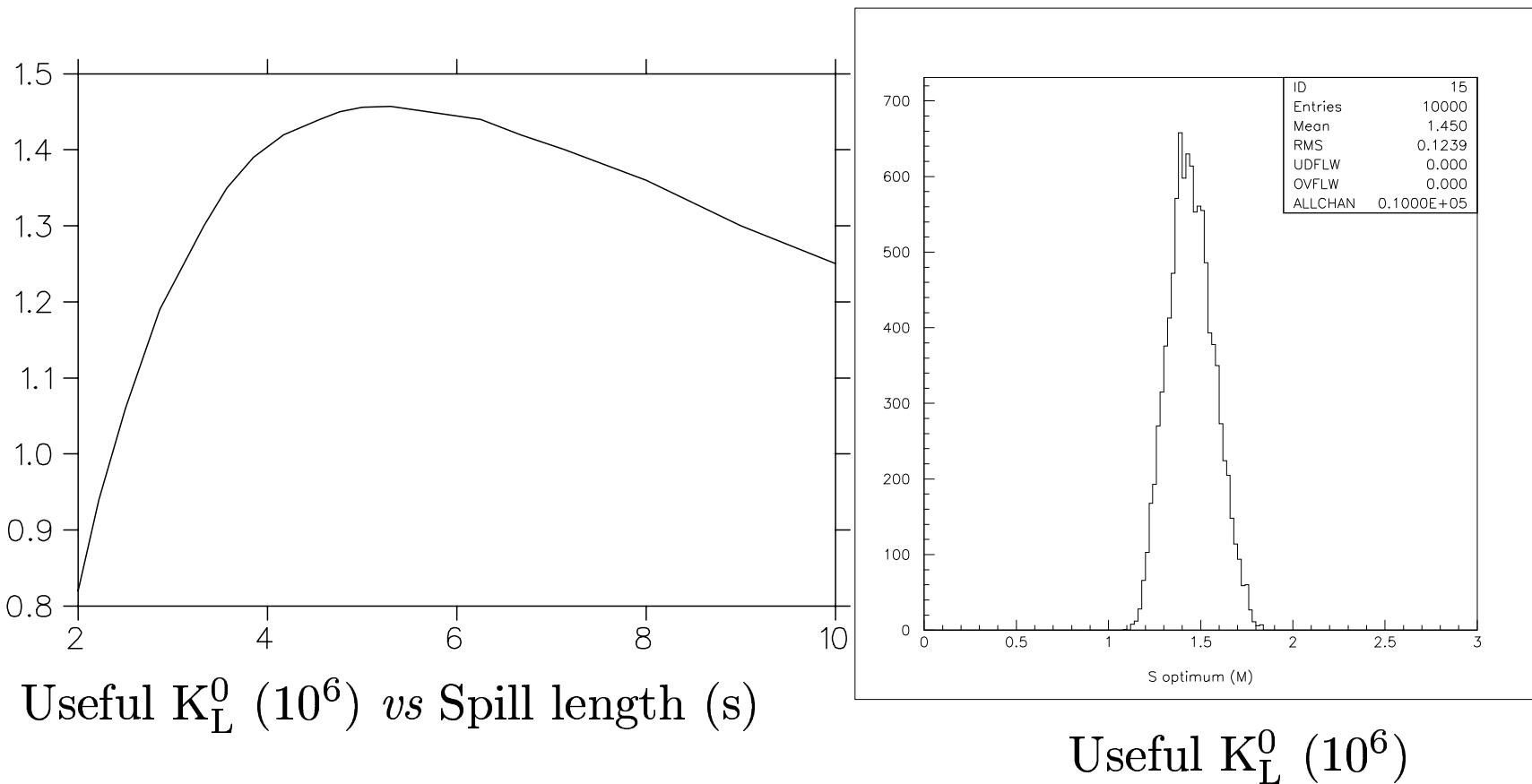
0.976 ± 0.002 Vetoing by K_L^0 in adjacent microbunch

0.985 ± 0.010 Vetoing by halo neutrons

0.986 ± 0.002 Vetoing by neutrons in catcher

Overall K_L^0 survival rate at optimal spill length of 5.3s is 0.40 (including rate-independent factors).

Spill length optimization taking losses into account



To make optimial use of the available protons per spill, we adjust the instantaneous rate taking into account all rate-dependent losses listed on the previous page. The LH figure shows the spill length that maximizes the number of useful K_L^0 decays in the fiducial volume per calendar second. RH figure shows effect of rate-dependent uncertainties on number of useful K_L^0 decays at optimal spill length.

Some outstanding issues

1. More robust estimates of losses from trigger and reconstruction with GEANT3 (in progress)
2. Continued study of E949 to understand issues of PV inefficiency.
3. Recovery of events lost due to catcher blindness

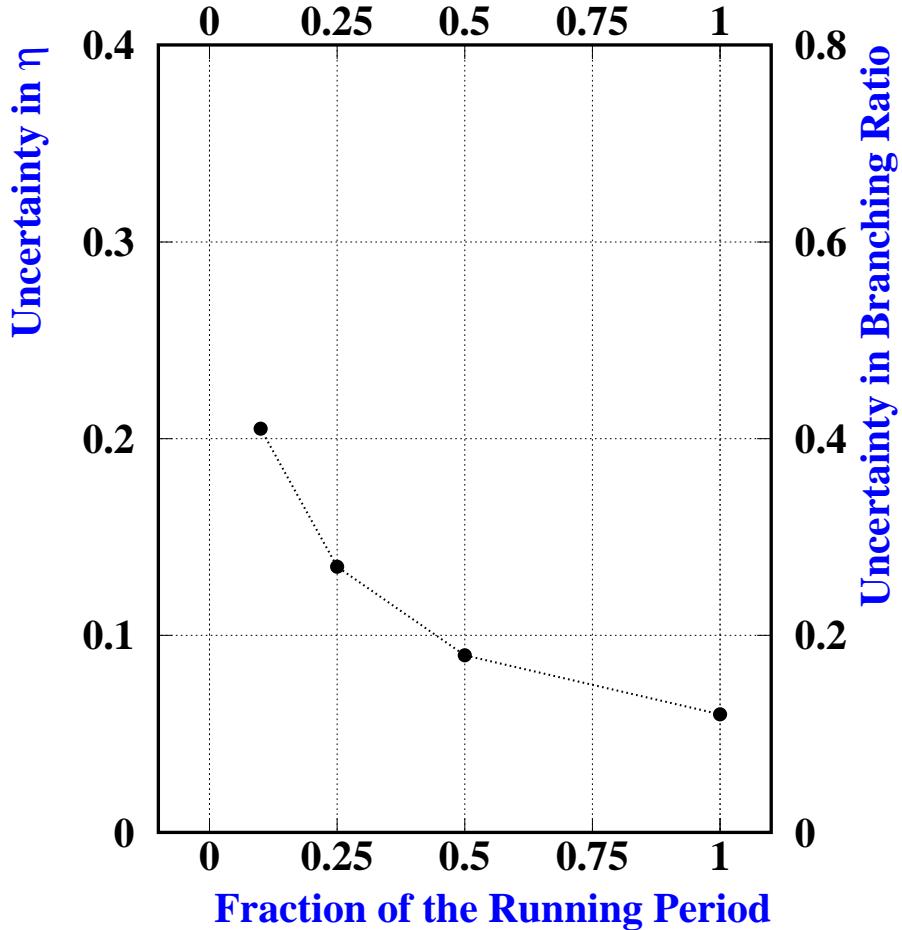
Uncertainties in overall expected acceptance

Based on measurements and calculations we assess these relative ranges on the following parameters.

Range	Parameter
1.0 ± 0.2	K_L^0 flux
1.0 ± 0.11	Survival factor due to other K_L^0 in microbunch
$1.0^{+1.0}_{-0.2}$	Effect of photon veto on acceptance
$1.0^{+0.3}_{-0.2}$	Effect of charged particle veto on acceptance
1.0 ± 0.2	Veto gate scale factor
1.0 ± 0.5	Neutron beam core
$1.0^{+1.0}_{-0.5}$	Neutron halo/beam
$1.0^{+1.0}_{-0.4}$	Neutron response factor

The ranges are taken into account into evaluating the expected precision on $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$.

$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ precision and sensitivity



A precision of $\pm 12\% (9\%, 16\%)$ on $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$ is evaluated with a likelihood method using all observed events up to a S/B of 0.3. The range of precision takes into account the uncertainties listed on the previous page.

Method	Signal	S/B
2 γ PR/CAL+OV	89	0.42
1 γ PR/BV	92	0.26
1 γ PR/CAL	20	0.38
All	200	0.33

We expect ~ 200 $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ events after 12000 hours of running will yield a precision of 12% on $\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$.